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14. ABSTRACT
Precise control of coupling between waveguides and resonant cavities enables realization of several novel and improved devices, including low-power modulators, switches, filters, and wavelength routers. The goal of this program is to theoretically and experimentally evaluate and develop schemes for efficient controlled coupling in optical polymer and semiconductor devices. Chip-based devices should be inexpensive, manufacturable, and can potentially be miniaturized and integrated with electronics. Technological progress under this grant has included development and optimization of a soft-lithography technique for replica molding of optical polymer devices, and a suite of III-V semiconductor fabrication techniques suitable for electrically driven structures. Optical polymer and semiconductor material systems have been employed to realize a large number of novel devices, including high-contrast tunable optical filters, low voltage Mach-Zehnder interferometers, and a compact, low power racetrack resonator switch based on controlled waveguide-resonator coupling.

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Low power optical modulation, high-contrast switching, critical coupling, waveguide-resonator coupling, ring resonator, filter, optical polymers, electrooptic polymers, III-V semiconductors

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Monolithic Waveguide Geometry for Voltage Controlled Switching and Routing of Optical Beams Based on Waveguide-Resonator Coupling

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Project Goals

Precise control of coupling between waveguides and resonant cavities enables realization of several novel and improved devices, including low-power modulators, switches, filters, and wavelength routers. The goal of this program is to theoretically and experimentally evaluate and develop schemes for efficient controlled coupling in optical polymer and semiconductor devices. Chip-based devices should be inexpensive, manufacturable, and can potentially be miniaturized and integrated with electronics.

Approach

The goals of the project will be accomplished in four phases, as follows: (1) Modeling, fabrication and testing of waveguides and ring resonators in optical polymers, indium phosphide (InP) based semiconductors, and silicon on insulator (SOI) substrates. (2) Demonstrate coupling between waveguides and microresonators. (3) Demonstrate control of coupling. (4) Optimization of working parts and final demonstration.

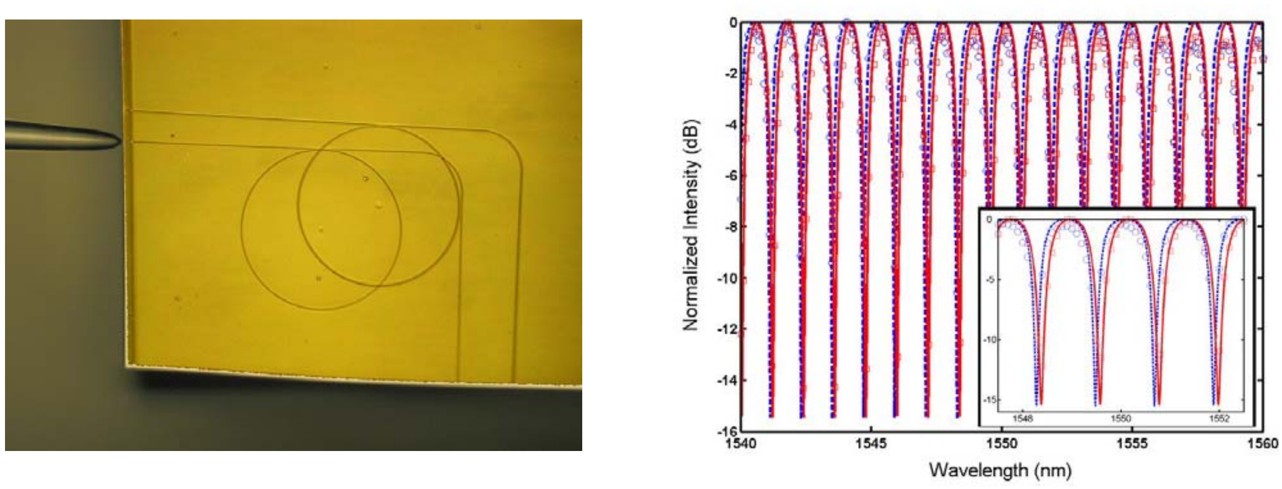
Accomplished Milestones

Initial work under this grant encompassed development of analytical and numerical techniques for analysis of coupled waveguide-resonator systems. Various numerical algorithms, including the finite-difference time domain and beam propagation methods, have been developed and applied in device design. Using these tools, a number of preliminary passive optical components, including bends, couplers, and ring resonators, have been designed. Basic fabrication techniques were subsequently used to generate several test devices in both polymer and semiconductor material systems, and a series of optical measurements confirmed the validity of the theoretical framework, thus permitting evaluation of material quality and fabrication tolerances.

Following these initial tests of our design tools, our center at Caltech developed a number of improved optoelectronic device fabrication techniques, in both optical polymer materials and InP based semiconductors. In particular, a soft-lithography technique for replica molding of optical polymer devices has been demonstrated. This method permits rapid replication, and molded devices have demonstrated outstanding fidelity to the original master from which the mold was cast. Several polymer devices molded on silica substrates have been tested, including an electrooptic polymer Mach-Zehnder interferometer, and a microring resonator optical filter. Furthermore, a free-standing microring optical filter, removed from a rigid silicon substrate, has been demonstrated. A number of important fabrication steps required for the processing of InP-based devices have been developed and optimized. These include electron beam and optical lithography, dielectric mask etching, semiconductor dry etching, deposition of planarization and electrical isolation layers, and electrical contact deposition. Semiconductor racetrack resonator filters operating near the critical coupling point were fabricated, and exhibited large extinction on resonance.

Fabrication techniques have also been perfected for SOI ring resonators. High resolution etching of resonators using a xenon difluoride chemically assisted ion beam etching system, as well as a chlorine inductively coupled plasma reactive ion etcher, was also demonstrated. Quality factor (Q) values of over 30,000 have been measured in such devices. Low waveguide losses have been obtained in SOI waveguides as the high refractive index contrast confines light well to small waveguides. Efficient couplers have been designed and fabricated to couple light onto the chip from a glass fiber, and from the chip back into a single-mode glass fiber. We have fiber pigtailed such high Q resonators, tuned them electrostatically by inserting them into a liquid crystal cell, and have investigated the optical power dependence of the resonator frequency. Liquid crystal polymers have been introduced to change the resonance frequency of SOI resonators. This approach has allowed us to define reconfigurable optical add/drop modulators (ROADMs).

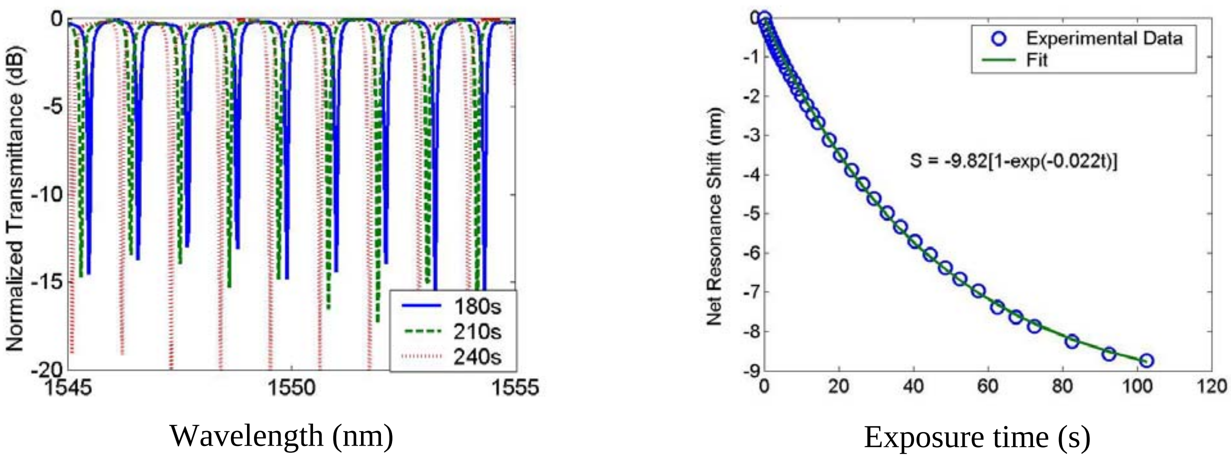
Some of the more recent work accomplished has included continued investigation of methods for dense integration of polymeric optical devices, for chip-scale technologies. One demonstration we have accomplished is the three-dimensional stacking of polymer ring resonator filters in multiple vertical layers, as shown in Fig. 1(a). By repeating the soft-lithography technique developed by our group in a repeated layer-by-layer fashion, complex optical systems can be synthesized from the bottom substrate upwards, with each layer potentially performing a different function. Figure 1(b) shows the optical transmission spectra of the dual-layer microring filter device. Both spectra show periodic notches with similar extinction ratios around -15 dB, indicating that the critical coupling condition is essentially satisfied for both layers in our design. Besides the extinction ratio, which is extremely sensitive to the accuracy of the fabrication process, the two spectra are also similar in terms of their free spectral range and resonance quality factor. The 0.1 nm offset between the two spectra was attributed to a difference between the effective refractive indices of the two rings, estimated to be on the order of 0.0001. The essentially identical microring resonator optical filters in this dual-layer device demonstrated the fidelity of the soft-lithography process, as well as the potential of three dimensional polymer integrated optics.



(a) (b)

Figure 1: (a) Optical microscope image of a multi-layer microring resonator filter. Input coupling was achieved using the tapered fiber shown on the left edge of the device. (b) Transmission spectra of microring optical filters in two layers of the microchip shown in Fig. 1. The experimental data are shown as solid circles for the lower layer, and as solid squares for the upper layer. The solid and dashed lines are numerical fits to the experimental data. The inset shows a magnified portion of the spectra near 1550 nm.

In order to achieve the best possible performance from polymeric optical devices and circuits, some form of post-fabrication trimming is generally necessary to compensate for the small but unavoidable deviations between the fabricated device and the ideal nominal design. We have demonstrated a simple means of trimming the optical transmission characteristics of a polymer ring resonator filter, using broadband visible light to expose a portion of the ring resonator post-fabrication. Exposure to visible light resulted in the photobleaching of the chromophore molecules within the polymeric material, which in turn produced a change in the refractive index of the exposed region. This refractive index shift provided a means of tuning both the resonance wavelength and the coupling coefficient of the ring resonator. Post-fabrication modification of the microring filter transmission spectrum is shown in Fig. 2(a), as a function of exposure time. After exposing the ring resonator for 240 s, the transmission extinction was changed from -15 dB to -35 dB, indicating that the device was tuned closer to perfect critical coupling. Figure 2(b) plots the observed net shift in the ring resonance spectrum as a function of time. The experimental data fits very well to an exponential model for the wavelength shift.



(a) (b)

Figure 2: (a) Tuning of the microring resonances by photobleaching. White light exposure times are indicated in the legend. The resonances shift by approximately -0.2 nm after each 30-s exposure with a light source intensity of approximately 35 mW/cm^2 over a 0.28 mm^2 area. (b) Net resonance wavelength shift as a function of exposure time. The exposure intensity is approximately 25 mW/cm^2 over a 0.12 mm^2 area. The experimental data are fitted with an exponential function as indicated, where *S* is the wavelength shift in nanometers, and *t* is the exposure time in minutes.

Most recently, work undertaken within the scope of this grant has been focused upon the demonstration of a device geometry for electrically controlled waveguide-resonator coupling, and the use of such a geometry for low-power optical switching, as shown in Fig. 3(a). To this end, a racetrack resonator was monolithically integrated with a variable directional coupler, i.e. a Mach-Zehnder interferometer, using the InGaAsP-InP material system. A schematic of the device as fabricated is shown in Fig. 3(b).

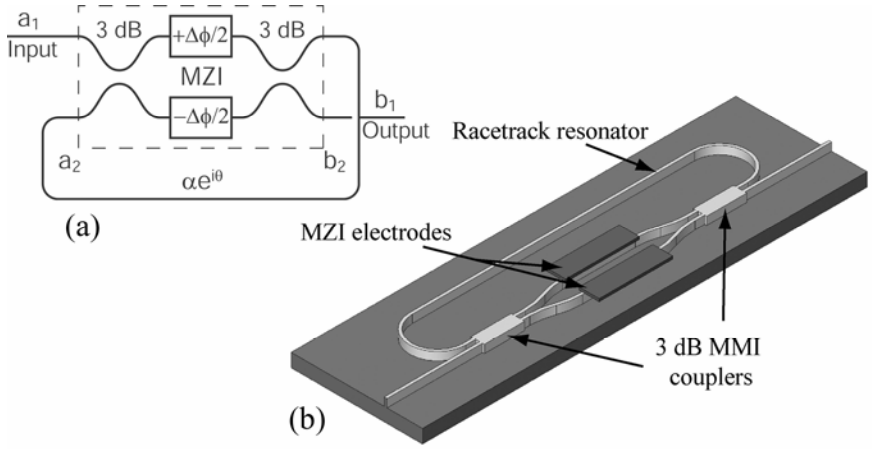


Figure 3: Hybrid MZI/racetrack resonator switch schematic drawings. (a) Illustration of relevant electric field components and relative phase between arms of MZI. (b) Illustration of the device geometry as fabricated (not to scale). The planar fabrication process utilized requires that the output waveguides of the MZI be uncrossed, in contrast to the crossed configuration shown in (a).

Thermooptic effects generated by ohmic heating were used to control the relative phase between the arms of the MZI, and thus, electrically control the coupling coefficient to the integrated racetrack resonator. The experimental transmission data shown in Fig. 4 illustrates that the optical power transmitted through the hybrid MZI/resonator geometry was successfully tuned through conditions of under, over, and critical coupling, and exhibited a maximum ON-OFF contrast ratio of 18.5 dB at critical coupling for TM polarization.

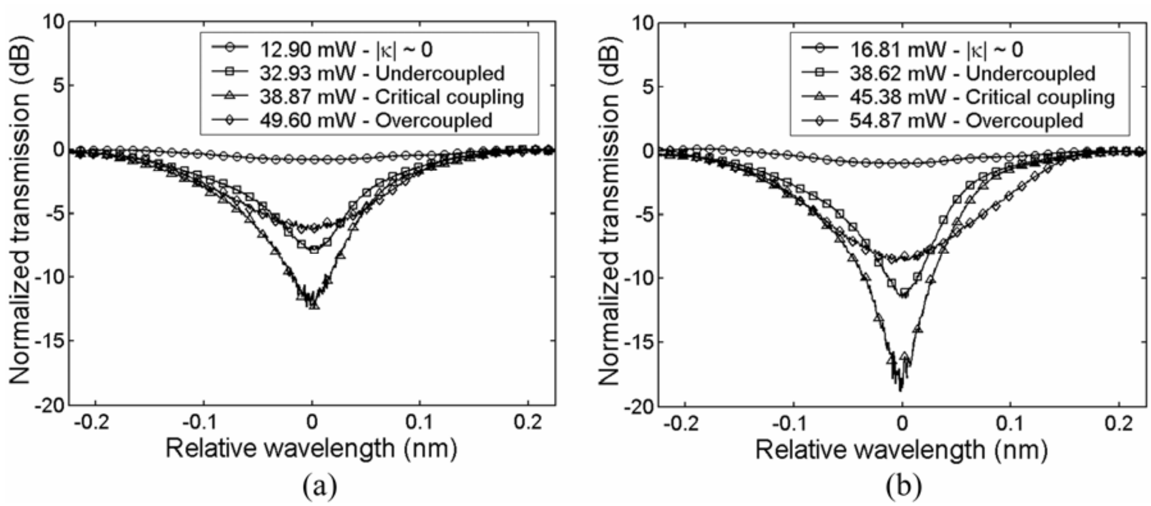


Figure 4: Normalized transmission illustrating the behavior of a single racetrack resonance as the MZI is tuned. The electrical power dissipated in a single MZI electrode appears in the legend. (a) TE polarized input, maximum contrast ~12 dB, switching power ~26 mW. (b) TM polarized input, maximum contrast ~18.5 dB, switching power ~29 mW.

A minimum switching power of 26 mW was measured for the hybrid device (for TE polarization), while a conventional MZI fabricated for comparison was measured to require 40 mW for complete switching. These results demonstrated the reduction in switching power theoretically predicted for this hybrid MZI/resonator geometry. The switching power can be reduced by an additional factor of two by operating the MZI in push-pull mode. In addition, straightforward reduction of the racetrack resonator loss can result in further reduction of the switching power by as much as an order of magnitude. The results of modulation response measurements, shown in Fig. 5, revealed a rise time of 1.8 μs and a 3 dB modulation bandwidth of 400 kHz, illustrating that this coupling-controlled racetrack resonator architecture has promise as a fast, low-power thermooptic switch. This switch may be easily integrated with other passive or thermally tunable InP-based devices, for compact photonic integrated systems.

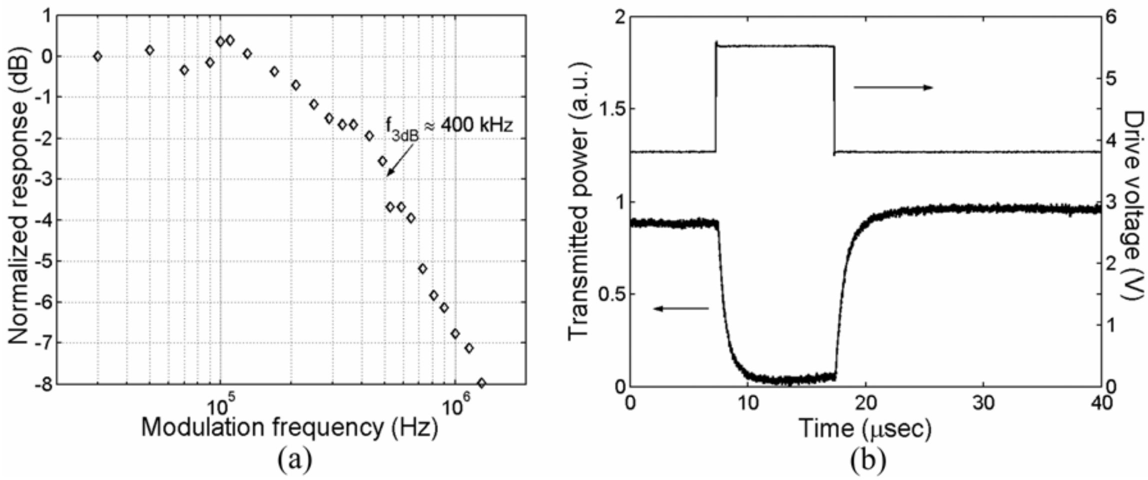


Figure 5: (a) Frequency domain modulation response, showing 3 dB small-signal bandwidth of 400 kHz. (b) Temporal response of normalized optical transmission to a 10 μs voltage pulse, showing a rise/fall time of ~1.8 μs.